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METAMATERIALS AND CONFORMAL ANTENNA TECHNOLOGIES

Srinivas Sridhar, Mehmet Dokmeci, Hossein Mosallaei, Latika Menon, Jeffrey Sokoloff, and Don Heiman

Northeastern University
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14. ABSTRACT
Metamaterials are artificially constructed materials. When electromagnetic waves propagate through metamaterials they display properties different from those found in natural materials. These different properties can include negative refraction (light is bent in the opposite direction from that expected from general laws of physics), flat lens focusing, and subwavelength imaging. The use of meta-materials to direct electromagnetic beams is a highly promising approach to overcome current limitations of conformal antennas by improving the radiation characteristics of antenna elements, especially those at the edge of phased array antennas.

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ABSTRACT

Meta-materials are artificially constructed materials. When electromagnetic waves propagate through meta-materials they display properties different from those found in natural materials. These different properties can include negative refraction (light is bent in the opposite direction from that expected from general laws of physics), flat lens focusing and sub-wavelength imaging. The use of meta-materials to direct electromagnetic beams is a highly promising approach to overcome current limitations of conformal antennas by improving the radiation characteristics of antenna elements, especially those at the edge of phased array antennas.

This project was centered on research and development of next generation metamaterials that are needed in optical and microwave radar antenna technologies. By directing electromagnetic beams, such materials can enormously improve detection the detection of enemy bodies and satellite communication with aircraft.
During this performance period, groundbreaking results were obtained in the following areas:

- Metamaterial Optical Components
- Theory of metamaterials based optical components
- Metamaterials, Nanofabrication and Sensors
- Metamaterial Antennas
- Reviews

Our work in this area has led to several major results, reported in 26 completed papers, and 3 patent applications, resulted in several invited and contributed presentations at international conferences and workshops, and has received extensive attention in the popular press, including write-ups in Nature, R&D Magazine, and other web and print outlets.

1.0 METAMATERIALS BASED OPTICAL COMPONENTS

The project developed several entirely new optical components including superlenses with superresolution imaging, and lenses that achieve superfocussing, using metamaterials.

1.1 SUPERRESOLUTION IMAGING USING A 3D METAMATERIAL NANOLENS

Superresolution imaging beyond Abbe's diffraction limit can be achieved by utilizing an optical medium or 'metamaterial' that can either amplify or transport the decaying near-field evanescent waves that carry subwavelength features of objects. Earlier approaches at optical frequencies mostly utilized the amplification of evanescent waves in thin metallic films or metal-dielectric multilayers, but were restricted to very small thicknesses ($\ll \lambda$, wavelength), and accordingly short object-image distances, due to losses in the material. We carried out the first experimental demonstration of superresolution imaging with a low-loss three-dimensional metamaterial nanolens consisting of aligned gold nanowires embedded in a porous alumina matrix. This composite medium possesses strongly anisotropic optical properties with negative permittivity in the nanowire axis direction, which enables the transport of both far-field and near-field components with low-loss over significant distances ($> 6\lambda$), and over a broad spectral range. We demonstrated the imaging of large objects, having sub-λ features, with a resolution of at least $\lambda/4$ at near-infrared wavelengths. The results are in good agreement with a theoretical model of wave propagation in anisotropic media. This work is due to appear in Applied Physics Letters (2010).

1.2 IMAGING WITH SUBWAVELENGTH RESOLUTION BY A GENERALIZED SUPERLENS AT INFRARED WAVELENGTHS

We experimentally demonstrated negative refraction by a photonic crystal prism and imaging of a point source by a photonic crystal slab at 1.5 µm wavelength. The photonic crystal structures were nanofabricated in a InGaAsP/InP heterostructure platform, and optical characterization was performed using a near-field scanning optical microscope. By designing a suitable lens surface termination, an image spot size of $0.12\lambda^2$ was achieved, demonstrating superlens imaging with subwavelength resolution well below Abbe's diffraction limit ($0.5\lambda^2$). This work was published in Optics Letters, V.34, Issue 13, P.1994-1996 (2009). (Selected for the July 27, 2009 issue of Virtual Journal of Nanoscale Science & Technology).

1.3 NANO-OPTICAL MICROLENS WITH ULTRA-SHORT FOCAL LENGTH USING NEGATIVE REFRACTION

We have experimentally realized an ultrashort focal length planoconcave microlens in an InP/ InGaAsP semiconductor two-dimensional (2D) photonic crystal with negative index of refraction (−0.7). At λ=1.5 µm, the lens exhibits ultrashort focal lengths of 12 µm (~8λ) and numerical aperture close to unity. The focused beam has a near diffraction-limited spot size of 1.05 µm (~0.68 λ) at full width at half maximum. Confirmation of the negative refractive index and focusing properties of the microlens was done by a 2D finite-difference time-domain simulations. Such ultrarefractive negative-index nano-optical microlenses can be integrated into existing semiconductor heterostructure platforms for next-generation optoelectronic applications. This work was published in Applied Physics Letters, V.93, P.053111 (2008). *(Selected for the August 18, 2008 issue of the Virtual Journal of Nanoscale Science & Technology)*

1.4 NANOENGINEERING OF A NEGATIVE-INDEX BINARY-STAIRCASE LENS FOR THE OPTICS REGIME

We showed that a binary-staircase optical element can be engineered to exhibit an effective negative index of refraction, thereby expanding the range of optical properties theoretically available for future optoelectronic devices. The mechanism for achieving a negative-index lens is based on exploiting the periodicity of the surface corrugation. By designing and nanofabricating a planoconcave binary-staircase lens in the InP/InGaAsP. We experimentally demonstrated at 1.55 μm that such negative-index concave lenses can focus plane waves. The beam propagation in the lens was studied experimentally and was in excellent agreement with the three-dimensional finite-difference time-domain numerical simulations. This work was published in Applied Physics Letters, V.92, P.243122 (2008).

2.0 THEORY OF METAMATERIAL BASED OPTICAL COMPONENTS

We developed several novel concepts for controlling light beams using metamaterials. New mechanisms were proposed for negative refraction and focusing, achieving superresolution imaging and superfocussing, and controlling the speed of light using metamaterials.

2.1 A NEW MECHANISM FOR NEGATIVE REFRACTION AND FOCUSING USING SELECTIVE DIFFRACTION FROM SURFACE CORRUGATION

Refraction at a smooth interface is accompanied by momentum transfer normal to the interface. We showed that corrugating an initially smooth, totally reflecting, non-metallic interface provides a momentum kick parallel to the surface, which can be used to refract light negatively or positively. This new mechanism of negative refraction was demonstrated by visible light and microwave experiments on grisms (grating-prisms). Single-beam all-angle-negative-refraction was achieved by incorporating a surface grating on a flat multilayered material. This negative refraction mechanism was used to create a new optical device, a grating lens. A planoconcave grating lens was demonstrated to focus plane microwaves to a point image. These results show that customized surface engineering can be used to achieve negative refraction even though the bulk material has positive refractive index. The surface periodicity provides a tunable parameter to control beam propagation leading to novel optical and microwave devices. This work was published in Optics Express, V.15, P.9166 (2007).

2.2 ALTERNATIVE APPROACH TO ALL-ANGLE-NEGATIVE-REFRACTION IN TWO-DIMENSIONAL PHOTONIC CRYSTALS

We showed that with an appropriate surface modification, a slab of photonic crystal can be made to allow wave transmission within the photonic band gap. Furthermore, negative refraction and all-angle negative refraction (AANR) can be achieved by this surface modification in frequency windows that were not realized before in two-dimensional photonic crystals [C. Luo *et al.*, Phys. Rev. B 65, 201104 (2002)]. This approach to AANR leads to different applications in flat lens imaging. Previous flat lens using photonic crystals requires object-image distance $u+v$ less than or equal to the lens thickness d, $u+v \leq d$. Our approach can be used to design a flat lens with $u+v=\sigma d$ with $\sigma >> 1$, thus being able to image large and/or far away objects. Our results are confirmed by finite-difference time-domain simulations. This work was published in Phys. Rev. A, V.76, P.013824 (2007).

2.3 NANOWIRE WAVEGUIDE MADE FROM EXTREMELY ANISOTROPIC METAMATERIALS

Exact solutions were obtained for all the modes of wave propagation along an anisotropic cylindrical waveguide. Closed-form expressions for the energy flow on the waveguide were also derived. For extremely anisotropic waveguide where the transverse permittivity is negative ($\varepsilon_\perp$<0) while the longitudinal permittivity is positive ($\varepsilon_{||}$>0), only transverse magnetic (TM) and hybrid modes will propagate on the waveguide. At any given frequency the waveguide supports an infinite number of eigenmodes. Among the TM modes, at most only one mode is forward wave. The rest of them are backward waves which can have very large effective index. At a critical radius, the waveguide supports degenerate forward- and backward-wave modes with zero group velocity. These waveguides can be used as phase shifters and filters, and as optical buffers to slow down and trap light. This work was published in Phys. Rev. A, V.77, P.063836 (2008).

2.4 SUPERLENS IMAGING THEORY FOR ANISOTROPIC NANOSTRUCTURED METAMATERIALS WITH BROADBAND ALL-ANGLE NEGATIVE REFRACTION

We showed that a metamaterial consisting of aligned metallic nanowires in a dielectric matrix has strongly anisotropic optical properties. For filling ratio $f < 1/2$, the composite medium shows two surface plasmon resonances (SPRs): the transverse and longitudinal SPR with wavelengths $\lambda t < \lambda l$. For $\lambda > \lambda l$, the longitudinal SPR, the material exhibits Re $\varepsilon_{||} < 0$, Re $\varepsilon_\perp > 0$, relative to the nanowires axis, enabling the achievement of broadband all-angle negative refraction and superlens imaging. An imaging theory of superlens made of these media is established. High performance systems made with Au, Ag, or Al nanowires in nanoporous templates were designed and predicted to work from the infrared up to ultraviolet frequencies. This work was published in Phys. Rev. B, V.77, P.233101 (2008).

2.5 SLOW MICROWAVE WAVEGUIDE MADE OF NEGATIVE PERMEABILITY METAMATERIALS

The framework for designing a slow light waveguide structure which operates in the GHz and up to THz frequencies was developed. The design for the structure consists of a dielectric core layer cladded with negative permeability metamaterials. The parameter space for the metamaterial has been identified for the waveguide to stop light and the negative permeability is achieved by split-ring resonator (SRR) metallic elements. A prototype structure operating at 8.5 GHz was proposed. Numerical simulations of electromagnetic waves interacting with SRRs have been performed to extract scattering parameters and a parameter retrieval method has been used to verify the designed window for negative permeability. This work was published in Microwave and Optical Technology Letters, V.51, No. 11, P.2705-09 (2009).

2.6 SLOW LIGHT, OPEN CAVITY FORMATION, AND LARGE LONGITUDINAL ELECTRIC FIELD ON SLAB WAVEGUIDE MADE OF INDEFINITE-INDEX METAMATERIALS

The optical properties of slab waveguides made of indefinite-index metamaterials were considered. The transverse permittivity is negative while the longitudinal permittivity is positive. At any given frequency the waveguide supports an infinite number of transverse magnetic (TM) eigenmodes. For a slab waveguide with a fixed thickness, at most only one TM mode is forward-wave. The rest of them are backward waves which can have very large refractive index. At a critical thickness, the waveguide supports degenerate forward- and backward-wave modes with zero group velocity. Above the critical thickness, the waveguide supports complex-conjugate decay modes instead of propagating modes. These slab waveguides can be used to make optical delay lines in optical buffers to slow down and trap light, to form open cavities, to generate strong longitudinal electric fields, and as phase shifters in optical integrated circuits.

2.7 STORING LIGHT IN ACTIVE OPTICAL WAVEGUIDES WITH SINGLE-NEGATIVE METAMATERIALS

We showed that a non-resonant planar waveguide consisting of a conventional dielectric cladded with single-negative metamaterials, supports degenerate propagating modes for which the group velocity and total energy flow can be zero if the media are lossless. However, absorptive losses will destroy the zero-group velocity condition for real frequency/complex wavevector modes. We showed that by incorporating gain G into the core dielectric, there exists a critical gain value *c G* at which we can recover the condition of zero group velocity, so that light pulses can be stopped and stored. This structure is simpler to achieve than double-negative metamaterials, has small footprint and can be incorporated into ultra-compact on-chip optoelectronics.

3.0 METAMATERIALS, NANOFABRICATION AND SENSORS

3.1 NEGATIVE INDEX METAMATERIALS BASED ON METAL-DIELECTRIC NANOCOMPOSITES FOR IMAGING APPLICATIONS

Negative index metamaterials were demonstrated based on metal-dielectric nanocomposites prepared using a versatile bottom-up nanofabrication approach. The method involves the incorporation of vertically aligned metal nanowires such as Au and Ag inside dielectric aluminum oxide nanotemplates. Optical absorbance measurements show resonance peaks corresponding to the transverse and longitudinal surface plasmon modes. A quantitative model based on effective medium theory is in excellent agreement with experimental data, and points to specific composite configurations and wavelength regimes where such structures can have applications as negative refraction media for imaging. This work was published in Appl. Phys. Lett., V.93, P.123117 (2008).

3.2 DESIGN AND IMPLEMENTATION OF SILICON BASED OPTICAL NANOSTRUCTURES FOR INTEGRATED PHOTONIC CIRCUIT APPLICATIONS USING DEEP REACTIVE ION ETCHING (DRIE) TECHNIQUE

We developed the fabrication of nano-optical elements by means of deep reactive ion etching (DRIE) technique (Bosch process) on a silicon-on-insulator substrate. The nano structures are fabricated in a two step process. The first consists of direct-writing nanoscale patterns on PMMA polymer by electron beam lithography. These nano patterns are then transferred to the silicon surface by a low temperature and low pressure DRIE process using PMMA as a mask. The low temperature and low pressure conditions in the DRIE process minimize scalloping in the nanoscale features. We found that the etch rate is highly dependent on the aspect ratio of the structure. We have used the DRIE method to fabricate a negative-index photonic crystal flat lens and demonstrated the focusing properties of this flat lens using a near-field scanning optical microscope. This work was published in NSTI-Nanotech 2008 Conference Publication (2008).

3.3 A HIGH ASPECT RATIO, FLEXIBLE, TRANSPARENT, AND LOW-COST PARYLENE-C SHADOW MASK TECHNOLOGY FOR MICROPATTERNING APPLICATIONS

We fabricated a flexible parylene-C shadow mask technology for creating microscale patterns on flat and curved surfaces. The smallest feature size of 4 μm is demonstrated and the technology is scalable up to full wafer size. With the addition of SU-8 pillars, we also demonstrated multi mask processing with an alignment accuracy of about 5-6 μm. To achieve the smallest features, a low temperature and high aspect ratio (>8:1) parylene etch process was also developed. Utilizing this shadow mask, we successfully patterned proteins and cells on various surfaces (glass,

PDMS, methacrylate) up to 9 times. This technology has potential applications for patterning proteins, cells and organic transistors on conventional and/or unconventional substrates. This work was published in Proceedings of the 14th International Conference on Solid-State Sensors, Actuators, and Microsystems, Lyon, France, June 10-14, 2007 (2007).

3.4 Three Dimensional Controlled Assembly of Gold Nanoparticles Using a Micromachined Platform

By using optical lithographic procedures, we fabricated a micromachined platform for large scale three dimensional (3D) assembly of gold nanoparticles with diameters of ~50 nm. The gold nanoparticles are formed into 3D low resistance bridges (two terminal resistance of ~40 Ω) interconnecting the two microelectrodes using ac dielectrophoresis. The thickness of the parylene interlevel dielectric can be adjusted to vary the height of the 3D platform for meeting different application requirements. This research represents a step towards realizing high density, three dimensional structures and devices for applications such as nanosensors, vertical integration of nanosystems, and characterization of nanomaterials. This work was published in Appl. Phys. Lett. 90, 083105 (2007).

3.5 A Three Dimensional Multi-walled Carbon Nanotube based Thermal Sensor on a Flexible Parylene Substrate

We developed the first design, fabrication and testing results from a three dimensional Multi-Walled Carbon Nanotube (MWNT) based thermal sensor fabricated on a flexible Parylene- C substrate. Parylene-C is an inert, biocompatible, optically transparent, room temperature deposited polymer with a high mechanical strength, yet is rarely used as a flexible substrate. By utilizing a 2 mask process, we have manufactured a versatile microplatform for nanoscale assembly and then by utilizing dielectrophoretic assembly, incorporate MWNTs onto the platform in a 3D manner. The MWNTs are next encapsulated using a thin Parylene-C layer that acts as an environmental barrier and in addition keeps the MWNTs intact. The temperature Coefficient of Resistance of the MWNT sensor is measured to be between -0.21% and -0.66% per degree. The thermal sensor is compact, is very high density and could potentially be used for diverse temperature sensing applications such as in wearable textiles, on non planar surfaces and for invivo applications. This work was published in 7th IEEE Conference on Nanotechnology, Hong Kong, China, pp. 1062-66, August 2-5, (2007).

3.6 A Three Dimensional Thermal Sensor Based on Single-Walled Carbon Nanotubes

We developed a novel three-dimensional thermal sensor based on Single-Walled Carbon Nanotubes (SWNTs) utilizing dielectrophoretic (DEP) assembly. The sensor is fabricated using a hybrid assembly technique combining top down (fabrication of the microplatform) and bottom up (DEP assembly) approaches. Encapsulating the structure with a thin (1µm) parylene layer protects it from the environment and also improves the contact resistance. Both single and multi finger assembly electrode structures have been utilized to manufacture the 3D thermal sensor and its thermal sensitivity is measured with a heated chuck. The resistances of the structures decrease more than 10% across a temperature range from 25°C to 65°C. The temperature coefficient of resistance for the SWNT-based thermal sensor is measured and ranged from -0.154 to -0.24% for the single electrode device and varied from -0.3 to - 0.57% for the multielectrode device. This work was published in Proceedings of the 14th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers '07), Lyon, France, pp. 1023-26, June 10-14, (2007).

3.7 A High Aspect Ratio Parylene Micro-stencil for Large Scale Micro-patterning for MEMS Applications

Patterning using a Shadow Mask or Stencil technique is increasingly being utilized for creating microscale patterns on conventional and unconventional surfaces. Previously reported micro-stencils made of rigid or polymeric membranes have various shortcomings and lack precise pattern definition. We introduced a reusable, high aspect ratio (HAR), flexible parylene-C micro-stencil technology. To realize this micro-stencil, we have also developed a high aspect ratio polymer etching technology using an ICP tool and with this process, demonstrate features as small as 4 μm. By utilizing SU-8 support pillars as alignment posts, we demonstrate multi mask alignment with a tolerance of 5-7 μm. The large Young's Modulus of the Parylene-C material allows the stencil to be reusable. This flexible parylene-C stencil technology will find applications in the fabrication of organic transistors and selective metal deposition onto fragile MEMS devices. This work was published in Society of Experimental Mechanics 8th International Symposium on MEMS and Nanotechnology, Springfield, MA, pp. 45-51, June 4-6, (2007).

3.8 A Micromachined Platform for Three Dimensional Dielectrophoretic Assembly of Gold Nanoparticles for Nanodevices

We reported a novel technological approach for three-dimensional (3D) assembly of gold nanoparticles with an average diameter of 52nm using dielectrophoresis (DEP). To realize the 3D assembly, we have designed and fabricated a versatile self-aligned micromachined platform which is applicable for assembling metallic nanoparticles and nanostructures. The assembly process is achieved at room temperature and is compatible with conventional semiconductor fabrication and large scale nanoassembly. The current-voltage curves obtained from the 3D gold nanoparticle bridges demonstrate that the assembly is functional with resistance values between - 26 and 118 Ohms. This method has applications in making high density three-dimensional interconnects, vertically integrated nano sensors and for in-line testing of manufactured conductive nanoelements. This work was published in Proceedings of the 2nd International Conference on Nano/Micro Engineered and Molecular Systems (IEEE-NEMS), Bangkok, Thailand, pp. 809-12, January (2007).

3.9 Three Dimensional Dielectrophoretic Assembly of Single-walled Carbon Nanotubes for Integrated Circuit Interconnects

We reported a novel technological approach for three dimensional (3D) assembly of single-walled carbon nanotubes (SWNTs) using dielectrophoresis (DEP). The two terminal resistance of the assembled SWNTs is ~ 545 Ohms. Encapsulation of the 3D structure with a thin layer of parylene-C protects it from the environment and keeps it intact. This directed assembly procedure is versatile, inexpensive, and achieved at room temperature. By utilizing a self-aligned three mask process, we demonstrate a 3D assembly/encapsulation method utilizing conductive SWNTs as the metallization material, parylene-C as the inter-level dielectric and the encapsulation layer. This technology is also applicable for vertical assembly of other conductive nanostructures and will enable 3D research in nanotechnology. This work was published in Proceedings of the 20th IEEE International Conference on Microelectromechanical Systems (MEMS), Kobe, Japan, pp. 823-26, January (2007).

3.10 A Reusable High Aspect Ratio Parylene-C Shadow Mask Technology for Diverse Micropatterning Applications

We developed a low cost, flexible and reusable parylene-C shadow mask technology for diverse micropatterning applications . The smallest feature size of 4 µm is demonstrated and the technology is scalable up to full wafer scale. With the addition of SU-8 pillars, we also demonstrate multimask processing with an alignment accuracy of about 4–9 µm. To achieve features with fine resolution, a low temperature and high aspect ratio (>8:1) parylene etch process is also developed. Utilizing this shadow mask, we successfully patterned proteins and cells on various surfaces (glass, PDMS, methacrylate). High pattern flexibility (structures with different shapes and dimensions are successfully patterned) and patterning on curved PDMS surfaces were also demonstrated. This technology has potential applications for patterning proteins, cells and organic transistors on conventional and/or unconventional substrates. This work was published in Sens. Actuators A: Physical, V.145-46, P.306-315 (2008).

4.0 METAMATERIAL BASED ANTENNAS

4.1 Characterization of Metamaterial-Based Electrically Small Antennas

The purpose of this work was to theoretically investigate the behavior of an electrically small antenna enclosed in a metamaterial sphere. We consider the use of magneto-dielectric and negative permittivity materials for constructing the small antenna. The Green's function for the evaluation of the input impedance was derived and the method of moment with Galerkin's procedure is used to determine the probe current from which the input impedance of the resonator is calculated. A physical insight is provided, and the effect of metamaterials for bandwidth enhancement was addressed. This work was published in Proceedings of the 2007 IEEE International Symposium on Antennas and Propagation, Honolulu, Hawai'i, USA, June 10-15, (2007).

4.2 Electrically Small Antennas Embedded in Metamaterials: Closed-Form Analysis and Physical Insight

The main goal of this work is to understand the behavior of electrically small antennas embedded in metamaterials. To do so, the Green's function for small-size antenna located in small-size metamaterial sphere was approximated, then by applying the method of moment with Galerkin's procedure the probe current and input impedance as a function of sphere radius, antenna length, and material properties were derived. The results clearly demonstrate that in most of the designs considering the first dominant mode is not sufficient and one needs to consider higher order terms in Green's function expansion to provide an accurate analysis for antenna performance. A physical insight is highlighted. This work was published in Proceedings of the 2007 IEEE International Symposium on Antennas and Propagation, Honolulu, Hawai'i, USA, June 10-15, (2007).

REVIEWS

Negative Refraction in Photonic Crystals
We reviewed the phenomenon of negative refraction (NR) by 2D photonic crystals (PCs) is demonstrated in microwave experiments. NR by PCs is observed in 2D parallel-plate waveguide and in 3D free space measurements. Results are in excellent agreement with band structure calculation and numerical simulation. This review appeared in "Physics of Negative Refraction and Negative Index Materials", edited by Clifford M. Krowne and Yong Zhang, Springer (2008).

Optical Properties of Nanowire Made of Indefinite Metamaterials
In this book chapter, optical properties of nanowires made of anisotropic metamaterials are considered. Exact solutions are obtained for all the modes of wave propagation along the anisotropic cylindrical waveguide. Closed-form expressions for the energy flow on the waveguide are also derived. For extremely anisotropic waveguide where the transverse permittivity is negative ($\varepsilon_{\perp}<0$) while the longitudinal permittivity is positive ($\varepsilon_{||}>0$), only transverse magnetic (TM) and hybrid modes will propagate on the waveguide. At any given frequency the waveguide supports an infinite number of eigenmodes. Among the TM modes, at most only one mode is forward wave. The rest of them are backward waves which can have very large phase index. At a critical radius, the waveguide supports degenerate forward- and backward- wave modes with zero group velocity. Above the critical radius, the nanowire supports complex-conjugate decay modes instead of propagating modes. These nanowires can be used as phase shifters and filters, to generate large longitudinal electric fields, to form optical delay line in optical buffers to slow down and trap light, and also to form open cavities in optical integrated circuits. This review appeared in “Handbook of Nanophysics”, edited by Klaus Sattler (2009)

Negative Refraction of Light by Periodically Corrugated Surfaces
Refraction is an interface phenomenon. At a smooth interface refraction is accompanied by momentum transfer normal to the interface. We show that corrugating an initially smooth, totally reflecting, non-metallic interface provides a momentum kick parallel to the surface, which can be used to refract light negatively or positively. This new mechanism of negative refraction is demonstrated in visible light and microwave experiments on grisms (grating-prisms). This negative refraction mechanism is used to create a new optical device, a grating lens. A plano-concave grating lens is demonstrated to focus plane waves to a point image in both microwave and optic frequencies. Single-beam all-angle negative refraction (AANR) is achieved by incorporating a surface grating on a flat multilayered material. Surface modification is also applied to two-dimensional photonic crystals. New window of AANR is discovered and flat lens imaging has been demonstrated. These results show that customized surface engineering can be used to achieve negative refraction even though the bulk material has positive refractive index. The surface periodicity provides an extra tunable parameter besides bulk dispersion engineering to control wave propagation, leading to novel microwave and optical devices. This review is due to appear in “Structured Surfaces as Optical Metamaterials”, Cambridge University Press (2010).

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4) A High Aspect Ratio, Flexible, Transparent, and Low-cost Parylene-C Shadow Mask Technology for Micropatterning Applications, S. Selvarasah, S. H. Chao, C.-L. Chen, D. Mao, J. Hopwood, S. Ryley, S. Sridhar, A. Khademhosseini, A. Busnaina, and M. R. Dokmeci, Proceedings of the 14th International Conference on Solid-State Sensors, Actuators and Microsystems, Lyon, France, June 10-14, 2007 (2007).

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12) Design and Implementation of Silicon Based Optical Nanostructures for Integrated Photonic Circuit Applications Using Deep Reactive Ion Etching (DRIE) Technique, S. Selvarasah, R. Banyal, B.D.F. Casse, W.T. Lu, S. Sridhar and M.R. Dokmeci, NSTI-Nanotech 2008 Conference Publication (2008).

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17) Nano-Optical Microlens with Ultra-Short Focal Length using Negative Refraction, B. D. F. Casse, W. T. Lu, Y. J. Huang and S. Sridhar, Applied Physics Letters, V.93, P.053111 (2008). (Selected for the August 18, 2008 issue of the Virtual Journal of Nanoscale Science & Technology)

18) A Reusable High Aspect Ratio Parylene-C Shadow Mask Technology for Diverse Micropatterning Applications, S. Selvarasah, S.H. Chaoa, C.-L. Chena, S. Sridhar, A. Busnaina, A. Khademhosseini and M.R. Dokmeci, Sens. Actuators A: Physical, V.145-46, P.306-315 (2008).

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20) Imaging with Subwavelength Resolution by a Generalized Superlens at Infrared Wavelengths, B. D. F. Casse, W. T. Lu, R. K. Banyal, Y. J. Huang, S. Selvarasah, M. R. Dokmeci, C. H. Perry, and S. Sridhar, Optics Letters, V.34, Issue 13, P.1994-1996 (2009).

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21) Negative Refraction in Photonic Crystals, W.T.Lu, P.Vodo and S.Sridhar, Book chapter in, "Physics of Negative Refraction and Negative Index Materials", edited by Clifford M. Krowne and Yong Zhang, Springer (2008).

22) Optical Properties of Nanowire Made of Indefinite Metamaterials, W.T. Lu and S. Sridhar, Book chapter in, "Handbook of Nanophysics", edited by Klaus Sattler (2009).

23) Negative Refraction of Light by Periodically Corrugated Surfaces, Wentao Trent Lu and Srinivas Sridhar, Book chapter in, "Structured Surfaces as Optical Metamaterials", Cambridge University Press (2010).

24) Superresolution Imaging Using a 3D Metamaterial Nanolens, B. D. F. Casse, W. T. Lu, Y. J. Huang, E. Gultepe, L. Menon, and S. Sridhar, To appear in Applied Physics Letters (2010).

Manuscripts under review

25) Slow light, open cavity formation, and large longitudinal electric field on slab waveguide made of indefinite-index metamaterials, W. T. Lu and S. Sridhar, Department of Physics and Electronic Materials Research Institute, Northeastern University, Boston, Massachusetts 02115, USA (2009).
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26) Storing light in active optical waveguides with single-negative metamaterials, W. T. Lu, Y. J. Huang, B. D. F. Casse, R. K. Banyal and S. Sridhar, Department of Physics and Electronic Materials Research Institute, Northeastern University, Boston, Massachusetts 02115, USA (2009).
(Submitted)

Patent Applications

1) "Anisotropic Metal-dielectric Metamaterials for Broadband All-angle Negative Refraction and Flat Lens Imaging" – Wentao Lu and Srinivas Sridhar, Converted to U.S. Patent Application Se. No. 12/220,445 on 7/24/08, currently pending.

2) "A method to slow or stop electromagnetic waves for use in optical and microwave communication systems" – Wentao Lu and Srinivas Sridhar, filed as U.S. Provisional Patent Application 61/150,490 on 2/6/09, currently pending.

3) "Three dimensional nanoscale circuit interconnect and method of assembly by dielectrophoresis", Busnaina,Ahmed, Dokmeci, Mehmet, R., Khanduja, Nishant, Selvarasah, Selvapraba, Xiong, Xugang, Makaram, Prashanth, filed as US. Provisional Patent Application PCTIUS2007/023573, 12/4/08, currently pending.

INVITED TALKS

"Imaging and Negative Refraction using Photonic Crystals", MRS Workshop on Metamaterials at the mill-, micro- and nano-scale, Boston, November 27, 2006.

"Photonic Crystal Metamaterials: New concepts in Imaging and Negative Refraction", SPIE West, Jan 22, 2007.

"Nanotechnology: An introduction to the science behind the revolution", Workshop on Nanotechnology and Public Policy: Basic Science, Applications, and Regulatory Implications, Northeastern University, May 2, 2007, Boston, MA.

"Photonic Crystal Metamaterials: New concepts in Imaging and Negative Refraction", DARPA workshop on Components for Metamaterials, May 3, 2007, Arlington, VA.

"Photonic Crystal Metamaterials: New concepts in Imaging and Negative Refraction", AFRL workshop on EM propagation in Challenging Media, May 8, 2007, Hanscom, MA.

Panelist Speaker, "Successful Careers - What Does It Take?", IGERT PI Workshop, May 16, 2007, Arlington, VA

"Left-Handed Light", Nanophotonics Symposium, Boston University, May 16, 2007, Boston, MA

"Optical Metamaterials: New Concepts In Negative Refraction And Imaging", 5th Symposium on Photonics, Networking and Computing", Salt Lake City, July 18, 2007.

"Nanomedicine: A new paradigm in diagnosis and therapy", Plenary talk, "New England Bioengineering Conference", Brown University, Providence, RI, April 5, 2008.

"Nano-optical superlenses using negative index metamaterials ", Keynote: Workshop on Metamaterials and Special Materials for Electromagnetic Applications", Uni. Naples, 12/8-19 /08.

"Nanoplatforms for Nanomedicine", 2nd Annual Unither Nanomedical & Telemedical Technology Conf, Quebec, 2/24/09.

"IGERT Nanomedicine Program at Northeastern University", NNI Workshop, "Regional, State, and Local Initiatives in Nanotechnology 2009", 4/ 1/ 2009.

"Nanoplatforms for Nanomedicine", Keynote: Materials and Processes for Medical Devices conference, Minneapolis, Aug 10, 2009.

"Nanoscale optics using Negative Index Metamaterials",2009 Nanoelectronic Devices for Defense and Security (NANO-DDS) Conference, Ft. Lauderdale, 9/2/-10/2/2009.

Panel Moderator, NIBIB-HHMI Workshop on Interdisciplinary Training, Chevy Chase, MD, Sept 30, 2009.

Panelist, Council of Graduate Schools Workshop on International Collaborations, Quebec City, July 13, 2009.

Contributed Presentations

"Negative Index Metamaterials Based on Metal Nanowire Arrays Electrodeposited in Nanoporous Alumina Templates", Latika Menon, WenTao Lu, Adam Friedman, Steven Bennett, Donald Heiman and Srinivas Sridhar, NSTI, Boston, MA, June 2008

"Au Nanowire Arrays for Negative Index Metamaterial Applications" L. Menon, W. Lu, A. Friedman, S. Bennett, D. Heiman and S.Sridhar, PIERS conference, Hangzhou, China, March 2008.

"Negative Index Metamaterials for Superlenses Based on Metal-Dielectric Nanocomposites", L. Menon, W. Lu, A. Friedman, S. Bennett, D. Heiman and S. Sridhar, APS, New Orleans, LA, March 2008

"Nanoscale optics using Negative Index Metamaterials", MRS Symposium on "Metamaterials--From Modeling and Fabrication to Application", Boston, Dec 1 2009.

PRESS REPORTS

Our work received extensive attention in the popular press, including write-ups in Nature, R&D Magazine, Physorg and several web and print outlets, some of which are listed below:

Nanotech Wire website, 08/27/08
Nanotechnology Development Blog, 08/29/08
Innovations Report, 08/07/08
Physorg website, 08/26/08
Nanotechnology website, 09/08
Medical Health Articles, 08/27/08
Mediafly website, 08/28/08
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R&D Magazine, 07/14/08
Northeastern Physics Department News, 08
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NewsWise, 07/07/08
Nature Journal, 08/28/08
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Nanotech Wire website, 07/08/08
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